Time evolution of Mach-like structure in a partonic transport model

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The time evolution of Mach-like structure (the splitting of the away side peak in di-hadron $\Delta\phi$ correlation) is presented in the framework of a dynamical partonic transport model. With the increasing of the lifetime of partonic matter, Mach-like structure can be produced and developed by strong parton cascade process. Not only the splitting parameter but also the number of associated hadrons (N_h^{assoc}) increases with the lifetime of partonic matter and partonic interaction cross section. Both the explosion of N_h^{assoc} following the formation of Mach-like structure and the corresponding results of three-particle correlation support that a partonic Mach-like shock wave can be formed by strong parton cascade mechanism. Therefore, the studies about Mach-like structure may give us some critical information, such as the lifetime of partonic matter and hadronization time.

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Recent RHIC experimental results indicated an exotic partonic matter may be created in central Au + Au collisions at $\sqrt{s_{NN}}$=200 GeV. When a parton with high transverse momentum (jet) passes through the new matter, it was predicted that jet will quench and lose energy, i.e. jet quenching [1]. At the same time, the lost energy will be redistributed into the medium [2, 3]. Experimentally the soft scattered particles which carry the lost energy have been reconstructed via di-hadron angular correlations of charged particles [4]. It is very interesting that Mach-like structure (the splitting of the away side peak in di-hadron $\Delta\phi$ correlation) has been observed in di-hadron azimuthal correlations in central Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [4, 5]. It was proposed that the structure is due to a Mach-cone shock wave generation, because jets travel faster than the sound in the new medium [6, 7]. However a gluon Cherenkov-like radiation model can also produce such structure [3, 8, 9]. Though so far some publications [10, 11, 12, 13] based on above different ideas come forth, quantitative understanding of the experimental observation has yet to be established.

In this work, a dynamical multi-phase transport model (AMPT) [14], that includes both initial partonic and final hadronic interactions, will be used to study the production mechanism of Mach-like structure. AMPT model is a hybrid Monte Carlo model which consists of four main processes: the initial conditions, partonic interactions, the conversion from partonic matter into hadronic matter and hadronic rescattering. The initial conditions, which include the spatial and momentum distributions of minijet partons and soft string excitations, are obtained from the HIJING model [1]. Excitations of strings melt strings into partons. Scatterings among partons are modelled by Zhang's parton cascade model [15], which at present includes only two-body scattering with cross section obtained from the pQCD with screening mass. In the string melting version of the AMPT model (we briefly call it as "the melting AMPT" model) [16], a simple quark coalescence model is used to combine partons into hadrons when all partons stop interactions. Dynamics of the subsequent hadronic matter is then described by a relativistic transport model. Details of the AMPT model can be found in a recent review [14]. It has been shown that in previous studies the partonic effect can not be neglected and the string melting mechanism is appropriate when the energy density is much higher than the critical density for the QCD phase transition [14, 16, 17]. In previous AMPT studies, parton cascade process will stop until partons do not interact again, and the hadronization takes place dynamically during the process. However, it is not very reasonable since the lifetime of partonic matter should be limited and decided by when the energy density (temperature) of reaction system enters into the critical value, in the view of Lattice QCD calculations[18]. In the present work, we will test different lifetimes of partonic matter, after which no partonic interactions are allowed and all left partons must coalesce into hadrons suddenly. It means that the partonic matter come to the critical point at a certain time, therefore the lifetime of partonic matter could be relative to hadronization time of reaction system. Two partonic cross sections, 10mb and 3mb, were used in our work.

Di-hadron correlations between the trigger hadrons and the associated ones were constructed by a mixing-event technique in our analysis, as experimenters did. The p_T window cuts for trigger and associated particles are $2.5 < p_T^{trig} < 4$ GeV/c and $1.0 < p_T^{assoc} < 2.5$ GeV/c. Both trigger and associated particles are selected within pseudo-rapidity window $|\eta| < 1.0$. The pairs of the associated particles with trigger particles in same events are accumulated to obtain $\Delta\phi = \phi - \phi_{trig}$ distributions. In order to remove the background which is expected to

mainly come from the effect of elliptic flow [4, 5], so-called mixing-event method is applied to simulate the background. In this method, we mixed two events which have very close centrality into a new mixing event, and extracted $\Delta\phi$ distribution which is regarded as the corresponding background. A zero yield at minimum assumption is adopted to subtract the background as did in experimental analysis [5, 19].

FIG. 1: (Color online) The $\Delta\phi$ correlations between trigger hadrons and associated ones ($2.5 < p_T^{trig} < 4.0$GeV/c and $1.0 < p_T^{assoc} < 2.5$ GeV/c) in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for different lifetimes of partonic matter in the melting AMPT model (10 mb) without hadronic rescattering. (a): lifetime = 0.5, 1.0, 1.5 fm/c; (b): lifetime = 2.0, 2.5, 3.0, 4.0, 5.0 fm/c. The $\Delta\phi$ correlations at different lifetimes have been shown with different makers for clarity, and corresponding solid lines are their two-Gaussian (a) or three-Gaussian (b) fits. (The dash line in (a) shows a three-Gaussian fit to the case of lifetime = 1.5 fm/c.); The inserted (c) in (b) shows a schematic illustration of Mach-like structure where the patonic Mach-like shock wave was excited by a jet travelling from x=0 fm in the positive x direction. (The different lines represent the partonic Mach-like shock fronts at different times.)

Figure 1 shows di-hadron $\Delta\phi$ correlations in Au + Au collisions at $\sqrt{s_{NN}}$=200 GeV for different lifetimes of partonic matter in the melting AMPT model without hadronic rescattering. In figure 1(a), no Mach-like structure is observed within ~ 1.0 fm/c partonic lifetime. However, Mach-like structure appears by longer parton cascade processes (more than ~ 1.5 fm/c), as shown in Fig. 1(a) and (b). (Note: we give two types of fits to 1.5 fm/c for the comparation.). It indicates that the formation of Mach-like structure needs a long duration of interacting partonic phase. Such partonic lifetime dependence is consistent with our previous results that the splitting parameter D (half distance between two Gaussian peaks on away side of di-hadron $\Delta\phi$ distributions) increases with number of participants, which is due to more long-lived partonic matters in the central collisions than in the peripheral collisions [19].

FIG. 2: (Color online) The dependences of splitting parameter D (a) and number of associated hadrons (b) on the lifetime of partonic matter in Au + Au collisions at $\sqrt{s_{NN}}$=200 GeV in the melting AMPT model without hadronic rescattering. Full points are for 10mb and open ones for 3mb. Triangles are for away side and circles for near side. Lines give the linear fit functions for N_h^{assoc} vs lifetime (solid: 10mb and dash: 3mb). Bands show the corresponding values at an infinite partonic lifetime, i.e. the results in our previous AMPT set [19].

Quantitatively, Figure 2 gives the dependences of splitting parameter D on the lifetime of partonic matter. It is observed that the splitting parameter D increases and then saturates with the lifetime of partonic matter, and the result with 10mb gives much bigger splitting parameters than that with 3mb, in comparison with experimental results. (But the opening angle of Mach-like structure can only be observed after the lifetime of 2 fm/c for 3mb.) It indicates that the production and development of Mach-like structure needs a long-lived and strong parton cascade process. It should be pointed out that the time evolution of energy density and d-quark temperature have been shown to reach the critical value around $\sim$ 5 fm/c in previous AMPT works [20]. The parton elliptic flow also saturates at this time in parton cascade evolution [16]. Here the corresponding saturation time of splitting parameter D is consistent with them. The hydrodynamical works [7, 11], which apply Cooper-Frye method for hadronization at some freeze-out temperature, have given good descriptions about Mach-like structure. Therefore, though partonic hadronization may be not an instantaneous phase transition but a durative process, the researches on Mach-like structure may shed light on some information about the lifetime of partonic matter and hadronization time. On the other hand, both numbers of associated hadrons (N_h^{assoc}) on near side and

away side increase with lifetime (Figure 2(b)). It is remarkable that the production rate of associated hadrons (dN_h^{assoc}/dt, the slope of N_h^{assoc} vs lifetime) has two different values before and after birth of Mach-like structure on away side, while that of associated hadrons on near side always keeps a constant. The Table I gives the production rates of associated hadrons on near side and away side in Au + Au collisions at $\sqrt{s_{NN}}$=200 GeV in the melting AMPT model without hadronic rescattering, which indicates a Mach-like shock wave has been created by strong parton cascade process and then its birth will boost its own growth quickly, therefore $'shock\ partons'$ may be ejected from the shock wave plentifully, especially for the case of bigger partonic cross sections. The inserted (c) in figure 1 give a schematic illustration of formation and development of the partonic Mach-like shock wave.

TABLE I: Production rates of associated hadrons on near side and away side in Au + Au collisions at $\sqrt{s_{NN}}$=200 GeV in the melting AMPT model without hadronic rescattering.

dN_h^{assoc}/dt	near side ($\leq$ 6 fm/c)	away side ($\leq$ 2 fm/c)	away side (2 $\sim$ 6 fm/c)
10 mb	0.35 $\pm$ 0.01	0.12 $\pm$ 0.01	0.69 $\pm$ 0.01
3 mb	0.18 $\pm$ 0.01	0.10 $\pm$ 0.01	0.26 $\pm$ 0.01

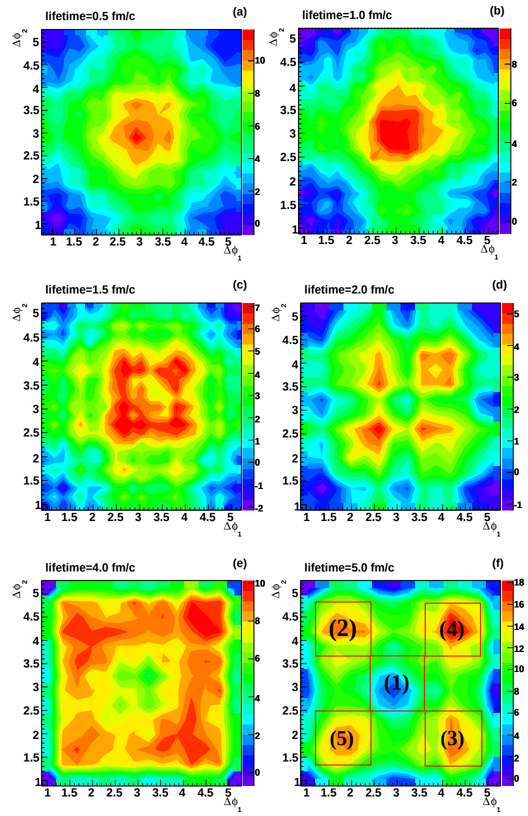

FIG. 3: (Color online) Background subtracted segmental 3-particle correlation areas ($1 < \Delta\phi_{1,2} < 5.28$) in central Au+Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV with different lifetimes of partonic matter in the melting AMPT model(10 mb) without hadronic rescattering.

The mixing-event technique has been used in our three-particle correlation analysis [21]. The p_T window cuts for trigger and associated particles are selected as $2.5 < p_T^{trig} < 4$ GeV/c and $1.0 < p_T^{assoc} < 2.5$ GeV/c, respectively. Both trigger and associated particles are selected within pseudo-rapidity window $|\eta| < 1.0$. In the same events, raw 3-particle correlation signals in $\Delta\phi_1 = \phi_1 - \phi_{trig}$ versus $\Delta\phi_2 = \phi_2 - \phi_{trig}$ are accumulated. Three background contributions are expected to be in the raw signal. The first one is $'hard-soft'$ background which comes from a trigger-associated pair combined with a background associated particle. It can produced by mixing a trigger-associated pair with another fake associated particle that is from different event. The second one is $'soft-soft'$ background which comes from an associated particle pair combined with a background trigger particle. It can be mimic by mixing an associated particle pair with another fake trigger particle that is from different event. The third one is a $'random'$ background, which are produced by mixing a trigger particle and two associated particles respectively from three different events. We require that the mixed events are from very close centralities which can be determined by impact parameter. In order to subtract the background from the raw signals, we normalize the strip of $0.8 < |\Delta\phi_{1,2}| < 1.2$ to zero.

Figure 3 gives the background subtracted segmental 3-particle correlation areas ($1 < \Delta\phi_{1,2} < 5.28$) in central Au+Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV, which shows three-particle correlations among one trigger particle and two associated particles on away side. There are three kinds of three-particle correlations in the area. Let us take segmental 3-particle correlation area with lifetime = 5.0 fm/c (Figure 3(f)) as an example. The first one is $'center'$ region ($|\Delta\phi_{1,2} - \pi| < 0.5$, i.e. region (1)) where three-particle correlation mainly comes from one trigger particle and two associated particles in the center of away side. The $'center'$ correlations show penetration ability of away jet. The second one is $'cone'$ region ($|\Delta\phi_1 - (\pi \pm 1)| < 0.5$ and $|\Delta\phi_2 - (\pi \mp 1)| < 0.5$, i.e. region (2) and region (3)) where three-particle correlation gives the correlation between one trigger particle and two associated particle which are respectively from different cones of away side. It was predicted that $'cone'$ correlations can be caused by Mach-cone shock wave effect when a jet goes faster than sound in the medium, shock wave would appear on away side. The third one is $'deflected'$ region ($|\Delta\phi_{1,2} - (\pi \pm 1)| < 0.5$, i.e. region (4) and region (5)) where three-particle correlation can reflect the correlation between one trigger particle and two associated particles from the same one of two peaks on away side in di-hadron $\Delta\phi$ correlations, which may be due to the sum of away-side jets deflected by ra-

dial flow and Mach-cone shock wave effect. It is found that there is only $'center'$ correlation before 1.5 fm/c, but $'cone'$ and $'deflected'$ correlations appear afterward and extend with the increasing of lifetime. Because the correlations within one cone-peak and between two cone-peaks on away side in di-hadron $\Delta\phi$ correlations are equivalent in a Mach-like shock wave scenario, the corresponding three-particle correlation strengths at (π-D,π-D), (π+D,π+D), (π-D,π+D) and (π+D,π-D) should be same. Actually, both $'cone'$ and $'deflected'$ correlations have similar strength in our results, which is consistent with the Mach-cone shock wave mechanism.

As we know, the AMPT model with the string melting scenario has presented good results of hadronic elliptic flow and even given the mass ordering of elliptic flow [16, 17] which has been well described by hydrodynamics model. It can be attributed to the big cross section of parton interaction in the AMPT model which leads to strong parton cascade that couple the partons together, it therefore induce the onset of hydrodynamics behavior [22]. Our present results show that the abundant and sequential partonic interactions can couple many partons together to exhibit the other collective behavior, i.e. partonic Mach-like shock wave [19, 21]. In Refs [10, 11], it was claimed that the main origin of Mach-cone structures is the lost energy which is deposited into a collective mode, i.e. $'hydro-mode'$. At the same time, we noticed that no Mach-like cone in di-hadron $\Delta\phi$ correlations has been seen in a dynamical hydrodynamics model in Ref. [12]. It should be mentioned that there are big differences between two dynamical models. The linearized hydrodynamical approximation is not applicable near jet region where the medium is with rapid variation of energy density and without adequate thermalization [7], while the parton cascade model works near and far way from jet region harmoniously. Since only two-body scatterings are included in the current AMPT model, we conclude that our results are due to the big partonic interaction cross sections which can transit the energy of high-p_T parton into a hydro-like pattern that stems from successive parton interactions.

We have not considered the effect from hadronic rescattering on Mach-like structure in the present work. However, it has been found hadronic rescattering is also important for Mach-like structure in our previous studies[19, 21]. We found that the effect of hadronic rescattering is weak for di-hadron correlations but considerable for three-particle correlations, for this p_T window cut. Fortunately, hadronic rescattering can not erase the correlations from a partonic shock wave, therefore the observed Mach-like structure in final state can carry the information about partonic Mach-like shock wave.

In conclusion, we used a partonic transport model to study the production mechanism of Mach-like structure with two- and three-particle correlation methods. Our results indicate that parton cascade mechanism can couple many partons together to exhibit a partonic Mach-like shock wave by strong partonic interactions. The partonic Mach-like shock wave is born at $\sim$ 1.5 fm/c and takes stable shape around $\sim$ 5 fm/c, and the birth of Mach-like shock wave can boost its own growth quickly by further parton cascade. Since the formation and development of Mach-like shock wave are sensitive to the strength of partonic interactions and the lifetime of partonic matter, the studies of Mach-like structure could be helpful to explore the characters of partonic interactions and the critical properties of reaction system, such as the lifetime of partonic matter and hadronization time.

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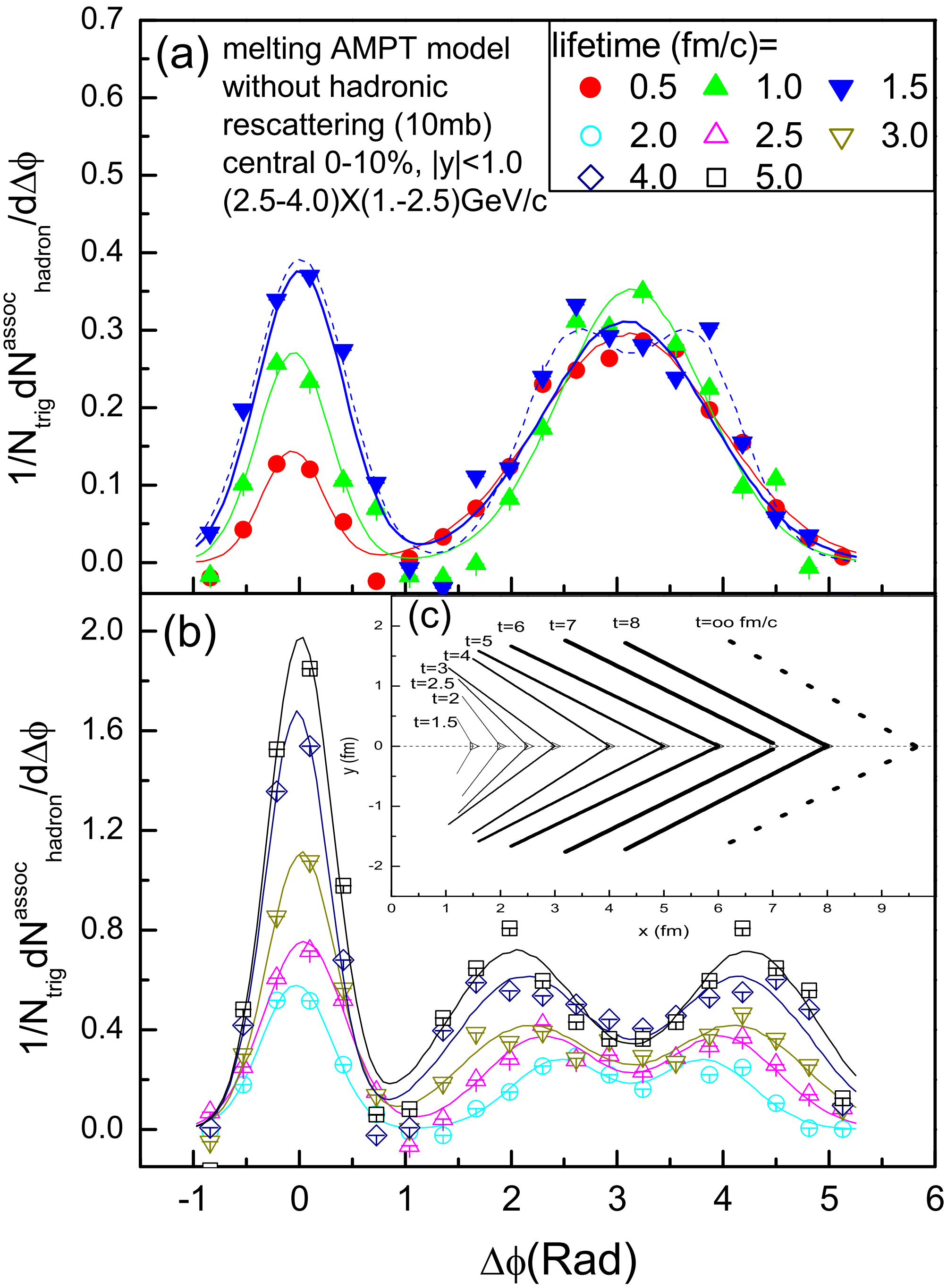
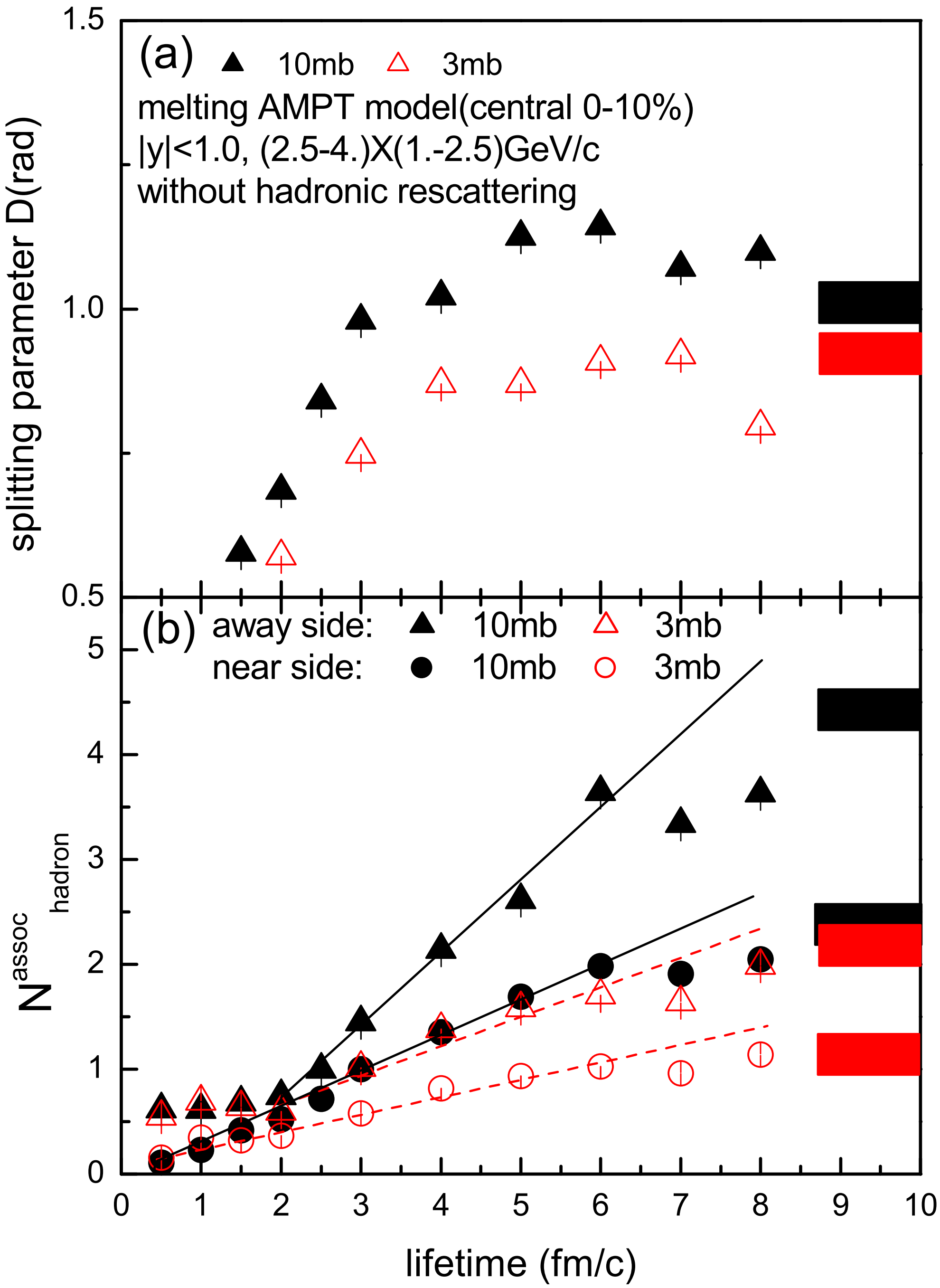


(a)
melting AMPT model
without hadronic
rescattering (10mb)
central 0-10%, |y|<1.0
(2.5-4.0)X(1.-2.5)GeV/c
lifetime (fm/c)=
0.5
1.0
1.5
2.0
2.5
3.0
4.0
5.0
(b)
(c)
t=1.5
t=2
t=2.5
t=3
t=4
t=5
t=6
t=7
t=8
t=oo fm/c
y (fm)
x (fm)
1/N_trig dN^assoc_hadron/dΔφ
Δφ(Rad)



(a)
10mb
3mb
melting AMPT model(central 0-10%)
|y|<1.0, (2.5-4.)X(1.-2.5)GeV/c
without hadronic rescattering
splitting parameter D(rad)
1.5
1.0
0.5
(b)
away side:
10mb
3mb
near side:
10mb
3mb
N^assoc_hadron
0
1
2
3
4
5
6
7
8
9
10
lifetime (fm/c)